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Alluvial groundwater recharge estimation in semi-arid environment using remotely sensed data

Victor Hugo R. Coelho [a,b,*], Suzana Montenegro [a], Cristiano N. Almeida [b], Bernardo B. Silva [a,c], Leidjane M. Oliveira [a], Ana Cláudia V. Gusmão [a], Emerson S. Freitas [b], Abelardo A.A. Montenegro [d]

[a] Geosciences and Technology Center, Federal University of Pernambuco, Recife, PE 50670-901, Brazil
[b] Water Resources and Environmental Engineering Laboratory, Federal University of Paraíba, João Pessoa, PB 58051-900, Brazil
[c] Atmospheric Sciences Department, Federal University of Campina Grande, Campina Grande, PB 58429-900, Brazil
[d] Agricultural Engineering Department, Federal Rural University of Pernambuco, Recife, PE 52171-900, Brazil

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ABSTRACT

Data limitations on groundwater (GW) recharge over large areas are still a challenge for efficient water resource management, especially in semi-arid regions. Thus, this study seeks to integrate hydrological cycle variables from satellite imagery to estimate the spatial distribution of GW recharge in the Ipanema river basin (IRB), which is located in the State of Pernambuco in Northeast Brazil. Remote sensing data, including monthly maps (2011–2012) of rainfall, runoff and evapotranspiration, are used as input for the water balance method within Geographic Information Systems (GIS). Rainfall data are derived from the TRMM Multi-satellite Precipitation Analysis (TMPA) Version 7 (3B43V7) product and present the same monthly average temporal distributions from 15 rain gauges that are distributed over the study area ($r = 0.93$ and $MAE = 12.7$ mm), with annual average estimates of 894.3 (2011) and 300.7 mm (2012). The runoff from the Natural Resources Conservation Service (NRCS) method, which is based on regional soil information and Thematic Mapper (TM) sensor image, represents 29% of the TMPA rainfall that was observed across two years of study. Actual evapotranspiration data, which were provided by the SEBAL application of MODIS images, present annual averages of 1213 (2011) and 1067 (2012) mm. The water balance results reveal a large inter-annual difference in the IRB GW recharge, which is characterized by different rainfall regimes, with averages of 30.4 (2011) and 4.7 (2012) mm year^{-1}. These recharges were mainly observed between January and July in regions with alluvial sediments and highly permeable soils. The GW recharge approach with remote sensing is compared to the WTF (Water Table Fluctuation) method, which is used in an area of alluvium in the IRB. The estimates from these two methods exhibit reliable annual agreement, with average values of 154.6 (WTF) and 124.6 (water balance) mm in 2011. These values correspond to 14.89 and 13.53% of the rainfall that was recorded at the rain gauges and the TMPA, respectively. Only the WTF method indicates a very low recharge of 15.9 mm for the second year. The values in this paper provide reliable insight regarding the use of remotely sensed data to evaluate the rates of alluvial GW recharge in regions where the potential runoff cannot be disregarded from WB equation and must be calculated spatially.

1. Introduction

In many parts of the world, groundwater (GW) is often considered the only available perennial water source, especially in arid and semi-arid regions (Usman et al., 2015). In Northeast Brazil, for example, alluvial GW plays an important role in supplying families and cities during the dry season. However, the semi-arid climate, which extends over large portions of this area, causes extreme water deficits because of low rainfall and high evapotranspiration (Montenegro and Ragab, 2010). These deficits can sometimes cause low water infiltration, which threatens aquifers.

GW recharge in both arid and semi-arid regions is relatively low and potentially irregular in time (Allison et al., 1994). Therefore, using a dense monitoring network to collect data has become necessary. These regions' observed data networks are often limited,

* Corresponding author at: Geosciences and Technology Center, Federal University of Pernambuco, Recife, PE 50670-901, Brazil.

E-mail addresses: victor-coelho@hotmail.com (V.H.R. Coelho), suzanam.ufpe@gmail.com (S. Montenegro), almeida74br@yahoo.com.br (C.N. Almeida), bbdasilva.ufpe@gmail.com (B.B. Silva), leidjaneoliveira@hotmail.com (L.M. Oliveira), villareluna@yahoo.com.br (A.C.V. Gusmão), emerson.sfreitas@hotmail.com (E.S. Freitas), abelardo.montenegro@yahoo.com.br (A.A.A. Montenegro).

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so hydrological models cannot be effectively used to make decisions (Khalaf and Donoghue, 2012). Moreover, the observed data often represent local characteristics. Nevertheless, the spatial variability in some places can be very high. The conversion of specific data from regionally distributed information has become a major challenge for most hydrological studies (Brunner et al., 2007).

In recent years, some innovative technologies, such as remote sensing (RS) and Geographic Information Systems (GIS), have played a key role in providing information for water resource management. Contributions to GW research have been more considerable from studies of recharge area delimitation (e.g., Jasrotia et al., 2007; Tweed et al., 2007; Elewa and Qaddah, 2011; Adiat et al., 2012; Agarwal et al., 2013; Awan et al., 2013; Nag and Gosh, 2013; Singh et al., 2013) and aquifer contamination vulnerability (e.g., Jamrah et al., 2007; Rahman, 2008; Huan et al., 2012; Huang et al., 2013; Linhares et al., 2014).

The RS approach is rather inconsistent at quantifying and estimating GW recharge because all current data from satellite images can only detect patterns and spatial processes that are related to resources on and above the Earth's surface. Because of these limitations, all efforts to calculate GW recharge will have to come from the use of indirect methods (Lucas et al., 2015). Consequently, all water recharge inferences should come from products that can represent the regional patterns of detection of other water balance (WB) parameters for GW modeling (Brunner et al., 2007), such as precipitation (e.g., Mashingia et al., 2014), evapotranspiration (e.g., Ruhoff et al., 2012), and runoff (e.g., Mahmoud, 2014). In principle, this result can be obtained from the interpretation of all remote sensing patterns over a deterministic distribution of input information based on cell-by-cell or zone databases (Brunner et al., 2007). Considering what was presented before, recent studies have merged satellite and terrestrial measurements to estimate regional GW recharge from the WB equation. However, recent studies have assessed GW recharge based on the difference between precipitation and evapotranspiration, and ignored changes in soil moisture and runoff (Crosbie et al., 2015). Considering this approach, studies have been conducted in the United States of America (Szilagyi et al., 2011), Hungary (Szilagyi et al., 2012), West Bank (Khalaf and Donoghue, 2012), Turkey (Gokmen et al., 2013), South Africa (Münch et al., 2013), Australia (Crosbie et al., 2015), and Southeast Brazil (Lucas et al., 2015). Unlike the aforementioned studies, the study by Usman et al. (2015) in a Pakistani agricultural region considered both the inputs and the resulting irrigation system outputs. Despite similarities in the methodologies, all these studies used different remotely sensed products in the WB equation. Table 1 provides an objective-focused tabular literature review of relevant studies on groundwater recharge using remotely sensed data.

The monitoring of GW data is incomplete in Brazil, especially in the northeastern semi-arid region, so access to field data is limited. Quantifying the renewal of depleted aquifers is therefore difficult, which can cause overexploitation of this resource along most hydrological periods. Because of this lack of data and the need for a systematic quantitative understanding of subsurface water resources, our aim is to integrate RS and GIS data to estimate the spatial distribution of GW recharge in a river basin in the semi-arid region of Northeast Brazil, that includes spatially varying runoff and soil moisture in the WB equation. The WB (RS) approach is compared to the water table fluctuation (WTF) method, which is applied to a specific area of the watershed where ground-based measurements were recorded from 2011 (wet year) to 2012 (dry year).

2. Material and methods

2.1. Study area

The Ipanema river basin (IRB) is the selected site for this study. This area is located in the Brazilian Northeast region, in what is known as the Drought Polygon. The region is subjected to pro-

Table 1
Summary of relevant literature on groundwater recharge estimation using remotely sensed data in relation to the proposed study. Note that the recent studies have assessed groundwater recharge mainly based on the difference between precipitation and evapotranspiration, ignoring changes in soil moisture and runoff. The symbols 'n.r.' and 'N/A' means 'not reported' and 'not available', respectively.

Study	Remotely sensed data and methods used	Location/climate/study size	Groundwater validation method
1. Szilagyi et al. (2011)	Difference between precipitation (PRISM database) and evapotranspiration (MODIS daytime surface temperature and ancillary climate data)	Sand Hills region, Nebraska, United States/Continental/n.r.	Base-flow/streamflow, groundwater modeling, and chloride mass balance
2. Szilagyi et al. (2012)	Difference between precipitation (Hungarian Meteorological Service grid-data) and evapotranspiration (WREVAP model, using MODIS daytime surface temperature and climate variables)	Danube-Tisza sand plateau region, Hungary/Continental/ $\sim$15000 km^2	N/A
3. Khalaf and Donoghue (2012)	Difference between precipitation (TMPA 3B43 product), evapotranspiration (SEBAL model using MOD09Q1 and MOD011A2 products), and runoff (assumed constant values for the study area)	West Bank/Mediterranean and dry desert conditions/5842 km^2	N/A
4. Münch et al. (2013)	Difference between precipitation (ARC-ISCW rainfall grids) and evapotranspiration (ET$_{MODIS}$ product, MOD16 product, and rainfall-runoff model)	Sandveld, South Africa/Semi-arid/647 km^2	Rainfall-runoff model and chloride mass balance by previous studies
5. Gokmen et al. (2013)	Difference between precipitation (TMPA 3B43 product combined with local rain gauge measurements) and evapotranspiration (SEBS model with MODIS products)	Konya river basin, central Anatolia, Turkey/Semi-arid/ 54000 km^2	N/A
6. Lucas et al. (2015)	Difference between precipitation (TMPA 3B42 product) and evapotranspiration (MOD16 product), with uncertainty analysis	Onça Creek, Southeastern Brazil/ Humid subtropical/$\sim$60 km^2	Water table fluctuation and water-budget using ground-based measurement
7. Crosbie et al. (2015)	Difference between precipitation (Bureau of Meteorology gridded product) and evapotranspiration (CMRSET product based on MODIS reflectance and short wave infrared data)	Murray-Darling basin, Southeastern Australia/ Mediterranean/29000 km^2	Water table fluctuation and chloride mass balance
8. Usman et al. (2015)	Difference between precipitation (TMPA product) and evapotranspiration (SEBAL model with MOD09A1 and MOD11A1 products), considering both the inputs and the resulting irrigation system outputs	Punjab, Pakistan/n.r./ $\sim$12000 km^2	Water table fluctuation and water-budget using ground-based measurements
9. This study	Difference between precipitation (TMPA 3B43 product), evapotranspiration (SEBAL model with MOD09A1 and MOD11A2 products), and runoff/soil moisture (NRCS method with Landsat 5/ TM image and ancillary data)	Ipanema river basin, Northeastern Brazil/Semi-arid/ 6217 km^2	Water table fluctuation